DETERMINATION OF THE DIFFUSION RATE OF INTERMETALLIC

COMPOUND Al_3Mg_4 INTO MAGNESIUM

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Forms of Diffusion into Solid Metal

Diffusion into solid metal is a complex process depending on numerous factors. Therefore, up to the present, there is no definite precise law, expressed by a mathematical formula, which would embrace and take into consideration all factors and complexities of this phenomenon.

All forms of diffusion may be broken into three large groups: first group; diffusion of gas into metal; second, diffusion of liquid metal into solid one; and third, diffusion of solid metal into solid.

This purely formal division corresponds to widely used industrial processes; gas carburization, cyaniding, and plating. However, each of these forms may be further broken into diffusion within the individual grain and diffusion along grain boundaries, i.e. on the grain surface or at the boundary separating two phases.

Diffusion within the grain may be again broken into (1) diffusion in the basal plane for metals with non-cubic crystal lattice, (2) diffusion in a direction perpendicular to the basal plane and (3) diffusion along the planes more closely packed with atoms or along the planes of most possible deformation of grain.

There is another entirely separate phenomenon of self-diffusion which may be defined as diffusion of atoms into their lattice. Determination of the rate of self-diffusion was developed by G. Hevesy who treated the surface of lead with a radioactive isotope of lead, observing its diffusion inwards. He studied this phenomenon and calculated the diffusion coefficient by measuring the radioactivity on the specimen surface with an electroscope, since radioactivity

decreases during diffusion of the lead isotope deep into the specimen.

In addition, A. Fry introduced a concept of pure and reactive diffusion (A. Fry, Stahl und Eisen, 1923, p. 1039). Pure diffusion embraces the phenomenon of mutual diffusion of metals in the solid state only in cases when these metals form solid solutions. In the case of limited mutual solubility, pure diffusion is determined by saturation concentration of the solid solution at a given temperature. Reactive diffusion is a phenomenon connected with the appearance of concentrations greater than maximum saturation concentration of the solid solution.

Complexity of the diffusion process is increased further by the author's observation that, in addition to penetration of the diffusing element into the metal, the reverse phenomenon occurs due to concentration increase and separation of individual phases at the boundary.

Laws of Diffusion

The law of diffusion was first developed by A. Fick in 1855. According to this law, the quantity of diffusing substance dm is proportional to the cross-section F of flow, concentration decrease $\frac{dc}{dx}$ and time $d\tau$: $dm = D.F \frac{dc}{dx} . d\tau.$

The constant D, known as a diffusion coefficient, is numerically equal to the amount of substance in grams, diffused per second through the area of 1 sq cm when the concentration drop is equal to unity. In spite of considerable practical limitations, Fick's law remains approximately justified for the formation of intermetallic compounds. In 1879, M. I. Stefan used it for measuring diffusion in liquid solutions of metals and compiled tables facilitating calculation of the diffusion coefficient for experimental conditions. These tables

were supplemented by W. Kovalki in 1894 and W. Jost in 1920. It is
possible to determine the rates of diffusion using Fick's law.

Three forms of diffusion rates have to be distinguished.

1. General rate of diffusion is measured by the amount of sub-
stance diffused per unit of time through cross-section F when the
concentration gradient is $\dfrac{dc}{dx}$. Formula for the diffusion rate is
as follows:

$$v = \frac{dm}{d\tau} = D.\,F.\,\frac{dc}{dx}$$

2. Concentration rate represents the increase in concentra-
tion per unit time in a cross-section located at a definite distance
from surface. It is expressed by Fick's second law:

$$v_c = \frac{dc}{d\tau} = D\,\frac{d^2c}{dx^2}.$$

3. Linear rate denotes the shift per unit time of the zone with
constant concentration into the depth of the substance to be saturated.
The linear rate is generally accepted in practice and literature as
the diffusion rate which, therefore, is expressed by none of the two
previously given equations, but by a third equation corresponding
to linear rate:

$$v = \frac{dx}{d\tau} = \tfrac{1}{2}\,k^{\frac{1}{2}}.\,\tau^{-\frac{1}{2}},$$

where k is a constant.

This rate of diffusion is determined by the shift of an arbitrary
boundary, having definite concentration and chosen depending on the
method of investigation. (Deduction of all equations is described
in "Diffusion of Metals" by V. S. Buganov and V. D. Neskuchayev and
"Diffusion of Elements into Solid Iron" by D. A. Prokoshkin, published
in 1937 and 1938, respectively).

The diffusion rate in solid bodies increases greatly with a rise
in temperature.

Weiss in his works (Revue de Metallurgie, 1924) gives the following expression for the diffusion rate in respect to temperature:

$$v = \frac{1}{\tau} = k \cdot a^{T},$$

where τ is time, T absolute temperature, k and a are constants determinable experimentally.

Tamman and Schonert (Zeitschz. anorg. allg. chemie, 1922) give an exponential expression for determining the diffusion coefficient D in relation to temperature: $D = e^{-a + b\,T}$, where a and b are constants and T is absolute temperature.

Arrhenius divides atoms (molecules) into active and passive types. Their activity is determined by the kinetic energy of motion, by oscillating motions or by the enhanced equation of energy which is attained by means of collisions or radiation. It is assumed that in solids only those atoms are able to move, whose oscillation amplitude is greater than the average oscillation amplitude of atoms; i.e. atoms with $r > r_0$ have a definite possibility for movement in a lattice, while this possibility for atoms with $r < r_0$ is small to the point of vanishing.

According to the Maxwell law of velocities distribution, the probable relative number of atoms with the oscillation amplitude $r > r_0$ will be equal to e, $\frac{E}{KT}$ where the magnitude E, heat of loosening, plays a role similar to that of activation heat in chemical reactions. Its values for alloys vary mainly in the range of 20,000-40,000 cal/mol; k is a universal Boltzmann constant equal to $1.37 \cdot 10^{-16}$ erg/deg or $3.27 \cdot 10^{-14}$ cal/deg; T is absolute temperature of diffusion. Hence, the quantity of substance diffusing per time unit, i.e. the diffusion coefficient, may be expressed as follows: $D = Ae^{-\frac{E}{KT}}$.

The value of A depends on temperature since it includes velocity of atoms, but this influence is considered negligible compared to change of potential, and, therefore, A is considered in the first approximation as a constant. Practice showed its applicability in a number of cases for processes of diffusion in the crystalline state (works by W. Seith and I. Laird, 1932, Zeitschrift fur Metalkunde).

in order to satisfy the purpose of this investigation.

The most essential requirements are as follows:

1. Contact must be sufficiently close to prevent the formation of oxide films and, especially, the existence of any air interlayer.

2. The method for establishing such a contact should be simple, approaching industrial possibilities.

3. Metallographic examination must be possible for clear observation of the $Al_3 Mg_4$ structure and further changes in structure along the phase diagram up to pure magnesium.

4. Penetration of $Al_3 Mg_4$ into magnesium must take place over a large area in order to make it possible to study this phenomenon by the metallographic method, and by X-ray analysis.

5. The method for obtaining contact should involve no modification of any of the properties of magnesium, i.g. grain coarsening.

All these requirements are necessary in order to attain the highest possible degree of precision in the investigations, keeping them close to practical production problems.

Method One

Solid magnesium in the shape of a cylinder 15 mm in diameter and 30 mm high is submerged into liquid or semiliquid $Al_3 Mg_4$. Melting points of magnesium and $Al_3 Mg_4$ are 651° and 463° C, respectively. It seems the difference of 188° must provide for the process of diffusion of liquid $Al_3 Mg_4$ into solid magnesium.

Fig. 1 represents a microscopic study of this process. The cylinder was kept in liquid $Al_3 Mg_4$ for 15 minutes at $470-475^\circ$ C. The structure of pure magnesium is sharply separated by a eutectic consisting of $Al_3 Mg_4$ and crystals of the solid solution $Al_3 Mg_4 \rightleftarrows Mg$.

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By its chemical composition, the alloy next to pure magnesium corresponds to 100% eutectic, i.e. 67% Mg + 33% Al. Farther inside of the eutectic, grains of $Al_3 Mg_4$ are inserted, gradually increasing and reaching 100% of composition.

This structure clearly illustrates the process of $Al_3 Mg_4$ penetration into solid magnesium. However, the method has a number of essential shortcomings. The intermetallic compound $Al_3 Mg_4$ in liquid state is subject to intensive oxidation and may ignite in the presence of a considerable supply of oxygen. Therefore, it has to be kept under the protection of fluxes. The cylinder of pure magnesium, during its sinking into molten $Al_3 Mg_4$, is covered with fluxes and, as a result, merging of the two substances does not begin simultaneously at all points on the cylinder. The eutectic, formed at the moment of merging, melts quickly since its melting point is 436° C, i.e. $34\text{-}38^\circ$ lower than the temperature of the experiment. The cylinder melts quickly to various extents at different points, making it difficult to calculate the rate of $Al_3 Mg_4$ penetration into the magnesium. This method also does not provide for the presence of $Al_3 Mg_4$ on magnesium in a large quantity which would permit having structurally free $Al_3 Mg_4$ on the surface during investigation of the process of its diffusion into magnesium.

Method Two

This method uses a different approach to the problem, attempting to establish close contact by pouring molten $Al_3 Mg_4$ into a hollow cylinder of pure magnesium. Several hollow cylinders were used for experiments. The dimensions were outside diameter 30 mm, inside diameter 15 mm, height, 60 mm. Liquid $Al_3 Mg_4$ was heated to $470\text{-}475^\circ$ C. First, the cylinder, filled with $Al_3 Mg_4$, was examined before any heat treatment. A photomicrograph of this cylinder is given in Fig. 2. It is clearly shown that no complete alloying was achieved; rather, there is a separation of the two components by an oxide film.

Four cylinders, similarly filled with molten $Al_3 Mg_4$, were held in a furnace at 420° C, each for a different period (5, 15, 50 and 100 hours).

Figure 3 gives a micrograph of cylinder No 3 after 50 hours in the furnace at 420° C, specimen having been etched. It shows grains of pure magnesium and very porous compound $Al_3 Mg_4$.

Further investigation revealed this method also unsuitable since there is no fusion over a large area, it takes place only at random points. The high tendency of $Al_3 Mg_4$ to oxidation in liquid state, in spite of preventive measures (melting under fluxes, pouring in SO_2 atmosphere, etc.) did not permit a complete and close contact and fusion of both components. In addition, liquid $Al_3 Mg_4$ dissolves much of the gases which, evolving at the moment of solidification, form pores and macro-bubbles. Oxidation occurs not only during pouring but also at the moment of solidification. The inside surface of the magnesium cylinders was also coated with oxide film regardless of their preparation. (Just before pouring, all cylinders were degreased and pickled with a weak solution of nitric acid.)

Method Three

Cylinders identical to those used in Method Two were tightly packed with a fine powder of $Al_3 Mg_4$ and sealed with magnesium plugs under a pressure of 3 tons. The plugs must hermetically seal the cylinders to prevent penetration of oxygen from the air. For this purpose, the upper inside part of cylinders and plugs were tapered at the same angle. Six cylinders prepared in this manner were held in a furnace at 420° C, each for a different period from 25 to 175 hours.

Upon heat treatment, each cylinder was cut into several parts, from which metallographic specimens were prepared.

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Examination of specimens in the unetched state revealed no diffusion of powdery $Al_3 Mg_4$ into magnesium. Realization of diffusion by the method described is quite possible, but it would be necessary to select a proper catalyst or maintain an inert atmosphere, or to increase the temperature. The development of this method would take considerable time and, therefore, further investigation was interrupted.

Method Four

A round cavity 30 mm deep and 10 mm in diameter, machined in ordinary aluminum, was filled with molten magnesium. All precautions, such as melting under flux, dusting with sulfur, etc., were taken to prevent possible oxidation during pouring. The cavity in the aluminum was preliminarily degreased with alcohol. Liquid magnesium, heated to $710-720^\circ$ C, introduces an amount of heat sufficient for melting a comparatively thick layer of aluminum, resulting in the formation of the intermetallic compound $Al_3 Mg_4$ on the side near the magnesium.

Figure 4 gives a photomicrograph of such an intermediate layer in the etched state. The width of this layer will vary depending on the temperature of the magnesium and preheating of the aluminum. The intermetallic compound $Al_3 Mg_4$ thus obtained, closely adjoining magnesium, is sufficiently free of oxide films and other impurities. Next to the grains of pure magnesium, there is a sharply outlined band of the eutectic changing into crystallines of $Al_3 Mg_4$.

Several specimens were heat treated as in methods two and three. Metallographic examination proved it possible to observe the diffusion of $Al_3 Mg_4$ into magnesium.

In order to corroborate the assumption that $Al3$, $Mg4$, but not Al, actually diffuses, a piece of pure aluminum was placed in a furnace at 420° C. After pouring liquid magnesium into its cavity, the aluminum piece was sectioned along magnesium insert.

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Upon holding in the furnace for several hours, the intermetallic compound $Al_3 Mg_4$ embedded between aluminum and magnesium, being intensively oxidized, expanded and partially squeezed the magnesium out of its space. This is shown in Figure 5 (left part).

Method Five

This method for obtaining close contact between $Al_3 Mg_4$ and magnesium employs the inverse procedure of the previous method. Liquid aluminum at 730° C was poured into a hollow cylinder of pure magnesium, which must be preheated to $350-400^\circ$ C to secure complete fusing. The inner walls of the magnesium cylinder must be degreased with alcohol and the oxide film ust be removed from the aluminum just before pouring. Flow of metal over the edge of the cylinder is not advisable. The liquid metal actually should not reach the edge, thus providing for free solidification and contraction.

The solidification shrinkage of aluminum (6.6%) is greater than that of magnesium (4.4%), and this is the only negative factor of the given method, which otherwise has a great many advantages.

The magnesium cylinders, after the liquid aluminum was poured, were heat treated as in the previous methods.

Micrographs of etched specimens show a boundary zone near the magnesium after holding in the furnace at 420° C for 100 hours (Figure 6) and for 150 hours (Figure 7). Both micrographs demonstrate a complete contact, absence of impurities and complete transition from 100% content of $Al_3 Mg_4$ to pure magnesium. Decomposition of the entectic and coagulation of its components are also noticeable. Formation of the intermetallic compound $Al_3 Mg_4$ by this method is certain. Oxidation of this compound is intensive upon its contact with atmospheric oxygen, as shown in Figure 5 (right part).

Method Six

Electrolytical deposition of aluminum on magnesium is impossible due to the more negative potential of the latter. Deposition of magnesium on aluminum is of no interest within the scope of this work.

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Therefore, an attempt was made to deposit aluminum on magnesium by cathode spraying. For this purpose, two polished specimens of pure magnesium and aluminum, degreased with alcohol, were placed 3-4 mm apart in vacuo approaching hundredths of one millimeter mercury column. The aluminum specimen served as a cathode. The entire installation was arranged according to a description in the paper "Cathode Sputtering," published in 1934 by Yu. B. Maslakov. However, due to technical reasons, a voltage of 5,000 v, and 18-20 ma current were used. The installation was in operation with a continuous and constant vacuum for a period over 20 hours. Coating of the magnesium with thin film was observed, but upon completing the experiment, when air was admitted under the vacuum bell, this film was instantly oxidized. Metallographic examination of a carefully prepared specimen did not give any result.

Of all methods here described, the fifth method was selected as most suitable for the purpose of this investigation.

Forty cylinders of 25 mm inside diameter, with a cavity 35 mm deep and with 10 mm thickness of walls and bottom were machined out of ingot magnesium. Molten aluminum was poured at 725° C into the magnesium cylinders preheated to $375-380^\circ$ C. These conditions were strictly maintained for all cylinders in order to obtain fusion of both components to an approximately identical extent along the entire contact surface. Four cylinders were cut for metallographic specimens, representing longitudinal, transverse and bottom sections of the cylinders.

Figure 8 presents a typical joining zone of $Al_3 Mg_4$ with magnesium. The specimen splits into two portions along its brittle component, i. e. $Al_3 Mg_4$; the second half, having no significance for this investigation, is not examined.

Diffusion of $Al_3 Mg_4$ in Regard to Time

Twelve cylinders were heat treated to study the effect of the time factor on the process of $Al_3 Mg_4$ diffusion into magnesium. All cylinders were held in a furnace at 420° C: 2 cylinders for five hours; next, two, for 25 hours; and other pairs for 50, 100, 125 and

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and 150 hours respectively. After heat treatment, metallographic specimens were cut out of similar parts of each cylinder. Microscopic examination of the specimens revealed that the process of diffusion is a complex phenomenon. Examination of the specimen without any heat treatment (Figure 8) reveals the following structure in the fusion zone; grains of intermetallic compound Al_3Mg_4 are surrounded with the eutectic and separated from the grains of pure magnesium by a narrow strip, evidently representing a solid solution $Al_3Mg_4 \leftrightarrows Mg$.

The specimen held at $420°$ C for 5 hours, shows no grains of Al_3Mg_4 (Figure 9) but reveals grains of solid solution, framed by the eutectic; this band is considerably wider, and the width of the light strip of solid solution $Al_3Mg_4 \leftrightarrows Mg$ is also considerably larger. Obviously, with deeper penetration of Al_3Mg_4, formation of the eutectic again takes place, mainly at grain boundaries, and grains of the solid solution attain their maximum concentration at given temperature and grow in volume and quantity.

In the case of the specimen held in the furnace for 25 hours (Figure 11), structure remains unaltered but partial decomposition of the eutectic is observed. The eutectic does not now form a continuous network; there are considerable breaks in the network and, seemingly, a dissolving of the eutectic; i.e. coagulation and spheroidizing of its components occurs. This process continued with the same intensity in the case of a 50-hour holding period (Figure 12). Holding for 100 hours was not realized for technical reasons. The specimen held in a furnace for 125 hours (Figure 13) shows complete decomposition of the eutectic into its components, complete isolation of Al_3Mg_4 in a separate zone and deeper penetration of Al_3Mg_4 included in the grains of solid solution.

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The specimen held for 150 hours demonstrates total complete-
ness of this process (Figures 14 and 15), showing the grains of
Al_3Mg_4 and grains of solid solution $Al_3Mg_4 \rightleftarrows Mg$, which have varied
concentration of Al_3Mg_4 in depth. Consequently, two processes take
place simultaneously: (a) increase in the amount of solid solution,
whereas the concentration of Al_3Mg_4 in solution gradually decreases
along the depth of penetration; (b) decomposition of the eutectic,
coagulation and spheroidizing of Al_3Mg_4 and formation of Al_3Mg_4
grains. In addition, formation of the eutectic proceeded along the
boundaries of solid solution grains.

Mathematical calculation of the diffusion rate can not depict
the entire complexity of this process and, therefore, investigation
has to be limited to a consideration of only one side of the process,
namely, penetration of Al_3Mg_4 into magnesium.

It is necessary to establish a penetration limit for plotting
the penetration depth-time curve. Metallographic analysis permits
determining this limit with sufficient precision. The limit of
total penetration may be calculated from the edge of the solid solu-
tion strip to the minimum presence of structurally free Al_3Mg_4
(Figures 8, 9, 10, 11, 12, 13 and 14). This total depth of penetra-
tion includes separate zones with sharply varied concentration of
Al_3Mg_4. The zone showing presence of the eutectic sharply differs
by concentration from the zone containing only the solid solution.
Therefore, it is necessary to calculate also the second zone without
the eutectic. Depth of penetration is presented in Table 1 and in
the graph, Figure 16.

TABLE 1

Depth of Al_3Mg_4 Penetration into Magnesium

Depending on Time

Time of Holding in Furnace	Total Depth in mm	Depth of the Zone Without the Eutectic
5 hours	0.125	0.023
25 hours	0.174	0.053
50 hours	0.105	0.068

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Time of Holding in Furnace	Total Depth, in mm	Depth of the Zone Without the Eutectic
125 hours	0.219	--
150 hours	0.233	--

A number of investigators (G. Ageyev, Tamman, Rock, Weiss and others) demonstrated experimentally that the depth of a layer will vary, in regard to time, according to the parabolic law if the process of diffusion follows Fick's law.

Their reasoning was as follows; the quantity of diffusing substance m, in a certain layer x, for a certain period τ will be equal to

$$m_1 = F_x \frac{c_1 + c_2}{2} = Fx_1c \text{ and } m_2 = Fx_2c, \text{ etc.}$$

Consequently, for the period of $\Delta \tau = \tau_2 - \tau_1$ the quantity of diffusing substance, when the layer thickness changes from x_1 to x_2, will be $\Delta m = m_2 - m_1 = Fx_2c - Fx_1c = Fc(x_2 - x_1) = Fc\Delta x$ or: $dm = Fcdx$.

From Fick's equation $dm = DF \frac{\Delta c}{x} d\tau$; hence, $DF \frac{\Delta c}{x} d\tau = Fcdx$, or $xdx = D \frac{\Delta c}{c} d\tau$.

The value of $\frac{\Delta c}{c}$ is constant, since we take a layer with certain constant concentration; the value of D, under certain conditions (temperature, medium, pressure), is assumed also to be constant.' Integration of the equation gives

$$\int_0^x xdx = D \frac{\Delta c}{c} \int_0^\tau d\tau$$

$x^2 = 2D \frac{\Delta c}{c} \tau$, replacing $2D \frac{\Delta c}{c} = k$, obtain: $x^2 = k\tau$

Let us find out to what extent the experimental data of Table 1 are in agreement with this law. For this purpose we will consider only the penetration depth for one zone, since transition from one zone to the other involves a sharp change in concentration. Let us make calculations for the zone without the eutectic.

Let us determine a constant k for 24 hours or one day; then, $k = x^2 = 0.05^2 = 0.0025$, where x is expressed in mm and τ in days (24 hour periods). Using the equation $x^2 = 0.0025 \tau$, let us find

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the thickness of the layer without eutectic:

for 5 hours: $x_5 = \sqrt{0.0025 \cdot \dfrac{5}{24}} = 0.0228$ mm

for 25 hours: $x_{25} = \sqrt{0.0025 \cdot \dfrac{25}{24}} = 0.051$ mm

for 50 hours: $x_{50} = \sqrt{0.0025 \cdot \dfrac{50}{24}} = 0.071$ mm

for 125 hours: $x_{125} = \sqrt{0.0025 \cdot \dfrac{125}{24}} = 0.113$ mm

for 150 hours: $x_{150} = \sqrt{0.0025 \cdot \dfrac{150}{24}} = 0.124$ mm

Comparison of calculated values for depths of the layer without the eutectic with those obtained experimentally is presented in Table 2.

Figure 16 gives a curve plotted according to theoretical calculations and experimental points.

TABLE 2

Depth of Al_3Mg_4 Penetration into Magnesium

Depending on Time

Time of Holding in Furnace	Depth of Penetration	
	Experiment	Calculation
5 hours	0.023	0.0228
25 hours	0.053	0.051
50 hours	0.068	0.071
125 hours	--	0.113
150 hours	--	0.124

Experimental data are in close agreement with calculations according to the parabolic law.

Determination of the Linear Rate of

Al_3Mg_4 Diffusion into Magnesium

The linear rate of diffusion is defined as penetration of a zone with certain constant concentration per unit time. The relation between the depth of penetration and time was previously accepted as $x^2 = k\tau$, or $x = k^{\frac{1}{2}} \tau^{\frac{1}{2}}$.

Differentiation of this equation gives: $dx = \frac{1}{2} k^{\frac{1}{2}} \tau^{\frac{1}{2}} \cdot d\tau$.

Divide left and right parts of the equation by $d\tau$;

then $V_1 = \dfrac{dx}{d\tau} = \frac{1}{2} k^{\frac{1}{2}} \tau^{-\frac{1}{2}}$, or $V_1 = \frac{1}{2} \dfrac{\sqrt{k}}{\sqrt{\tau}}$

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Let us calculate the linear rate of diffusion of Al_3Mg_4 into

magnesium using the constant k previously determined. For 6 hours

in the furnace the linear rate of diffusion will be

$$V_1 = \tfrac{1}{2} \cdot \frac{\sqrt{0.0025}}{\sqrt{0.25}} = \tfrac{1}{2} \cdot \frac{0.05}{0.5} = 0.05 \frac{mm}{day} = 0.579.10^{\frac{-7 \, cm}{sec}}$$

[read as $0.579 \cdot 10^{-7} \frac{cm}{sec}$ etc.]

for 24 hours: $V_1 = \tfrac{1}{2} \cdot \frac{\sqrt{0.0025}}{\sqrt{1}} = 0.025 \frac{mm}{day} = 0.288.10^{\frac{-7 \, cm}{sec}}$

for 48 hours: $V_1 = \tfrac{1}{2} \cdot \frac{\sqrt{0.0025}}{\sqrt{2}} = 0.0177 \frac{mm}{dya} = 0.205.10^{\frac{-7 \, cm}{sec}}$

for 96 hours: $V_1 = \tfrac{1}{2} \cdot \frac{\sqrt{0.0025}}{\sqrt{4}} = 0.0125 \frac{mm}{day} = 0.144.10^{\frac{-7 \, cm}{sec}}$

for 120 hours: $V_1 = \tfrac{1}{2} \frac{\sqrt{0.0025}}{\sqrt{5}} = 0.0112 \frac{mm}{day} = 0.129.10^{\frac{-7 \, cm}{sec}}$

for 144 hours: $V_1 = \tfrac{1}{2} \cdot \frac{\sqrt{0.0025}}{\sqrt{6}} = 0.0102 \frac{mm}{day} = 0.118.10^{\frac{-7 \, cm}{sec}}$

These values are graphically represented in Figure 17. It is

necessary to remember that each value, calculated by this method,

represents the rate of Al_3Mg_4 diffusion in the zone of solid solu-

tions at temperature of 420° C.

CONCLUSIONS

The following conclusions may be drawn on the basis of this

investigation: (1) A method was developed for establishing contact

between intermetallic compound $Al_3 Mg_4$ and solid magnesium to in-

vestigate the processes of diffusion of Al_3Mg_4 into magnesium.

(2) The diffusion of one component into another, being connected

with the formation of new phases, is a complex phenomenon. The proc-

ess proceeds in two antipodal directions. With an increase of time

elapsed, decomposition of the eutectic into its basic components takes

place, an increase of the zone of solid solution $Al_3 Mg_4 \rightleftarrows$ Mg and

separation of its second component Al_3Mg_4 into a structurally-free

constituent occurs. (3) The relationship was established between

the depth of penetration (mainly for the zone of solid solution) and

time. It was found that the penetration depth, as a function of time,

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for the zone of solid solution is in good agreement with Fick's law.
(4) On the basis of Fick's law, the linear rate of diffusion of
Al_3Mg_4 in magnesium was determined for the zone of solid solution
at a temperature of $420°$ C. (5) The linear rate of diffusion and
effect of the time factor on penetration are at their maximum dur-
ing the initial 10-16 hours. This period is most appropriate for
production processes, such as homogenizing, holding at hardening
temperature, etc.

The present investigation puts forward a number of new prob-
lems, such as the rate of diffusion not only in cast but also in
deformed magnesium, influence of the grain size of magnesium on
diffusion and also the effect of the crystalline lattice of a dif-
fusing component on the process of diffusion. Works on these prob-
lems are scheduled for 1939.

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Captions for Illustrations

Figure 1. Magnification x 50

Figure 2. Magnification x 150

Figure 3. Magnification x230

Figure 4. Magnification x 150

Figure 5. Formation of the Intermetallic Compound Al_3Mg_4 Between
Magnesium and Aluminum

Figure 6. Magnification x 150

Figure 7. Magnification x 150

Figure 8. Without Heat Treatment x 132.5

Figure 9. Held in the Furnace at $420°$ C for 5 hours x 132.5

Figure 10. Held in the Furnace at $420°$ C for 5 hours x 425

Figure 11. Held in the Furnace at $420°$ C for 25 hours x 132.5

Figure 12. Held in the Furnace at $420°$ C for 50 hours x 132.5

Figure 13. Held in the Furnace at 420° C for 125 Hours x 132.5

Figure 14. Held in the Furnace at 420° C for 150 Hours x 132.5

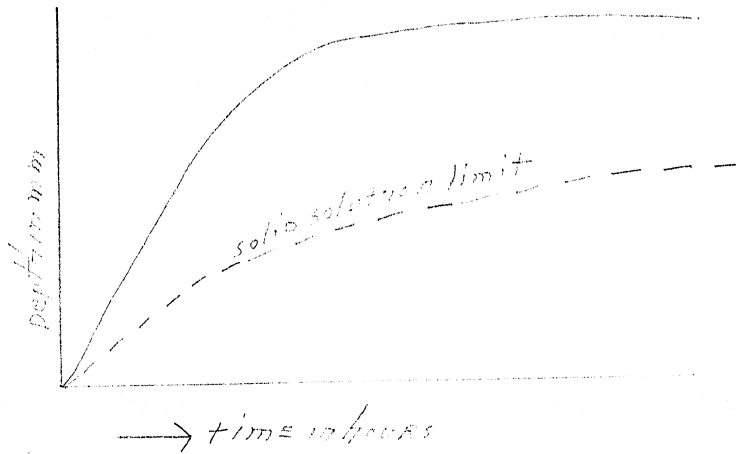Figure 15. Held in the Furnace at 420° C for 150 Hours x 425
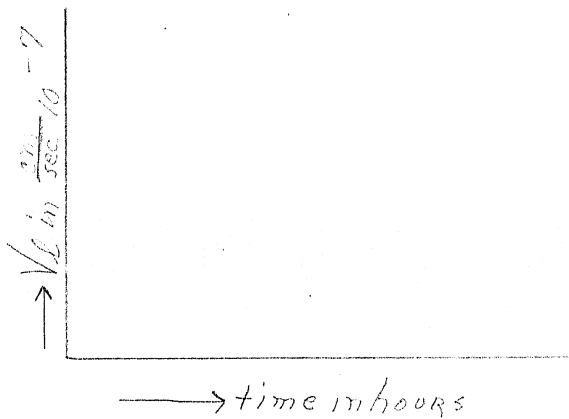
Figure 16

Figure 17